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THE INFRARED SIGNATURE OF BREAKING WAVES

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Abstract. The ability to measure the strength, or scale, of wave breaking in the open ocean remains elusive. Recent measurements of the infrared signature of wave breaking suggest that quantitative information about the breaking process can be provided by infrared techniques.

Key words: wave breaking, infrared sea surface temperature, ocean skin layer

1 Introduction

Despite the success of laboratory measurements of the dissipation due to wave breaking (Rapp and Melville, 1990), the ability to measure the strength, or scale, of breaking in the open ocean remains elusive. Previous authors have suggested that microwave and acoustic remote-sensing techniques may be used to characterize wave breaking dynamics (Melville *et al.*, 1988). In this paper, we review the subject of the infrared signature of wave breaking and present recent measurements using an infrared imager which suggest that infrared techniques can provide a measure of the scale of individual breaking events.

The breaking of deep water surface waves momentarily disrupts the otherwise continuous free surface that defines the air-sea interface. Vertical heat flux across this interface occurs by molecular conduction through a surface boundary, or 'skin', layer which has been estimated to be less than a millimeter thick (Robinson *et al.*, 1984). For conditions of net upward heat flux, the temperature gradient across this layer causes the skin temperature of the ocean to be less than the bulk temperature immediately below by a few tenths of a degree Celsius. The effect is most dramatic at night, when differences between the skin and bulk temperature can be as much as 0.5°C. An infrared radiometer operating at wavelengths of 8–12 microns has an effective measurement depth of roughly 10 microns, well within the skin layer. If this cool skin is momentarily disrupted, an infrared radiometer will register a rapid increase in temperature followed by a gradual decrease as the skin layer reestablishes itself.

A natural candidate for disruption of the skin layer is a breaking wave. The effect of breaking waves on infrared sea surface temperature measurements has been reported by previous investigators (Ewing and McAlister, 1960; Gasparovic *et al.*, 1974; Simpson and Paulson, 1980). In an attempt to simulate the surface disruption due to breaking, Ewing and McAlister (1960) directed a submerged pump at the sea surface beneath an infrared radiometer. When the surface was disturbed 'in the manner of a bubbling spring', the infrared temperature was approximately equal to the subsurface temperature measured by a thermistor at a depth of 15 cm.

When the pump was turned off, the infrared temperature returned to its normal value in about 5 s. Their observation that a "less intense disturbance failed to produce a measurable effect" suggests that there may be a turbulence threshold below which the cool skin remains intact.

When they measured actual breaking waves, Ewing and McAlister (1960) found a 'momentary' rise in surface temperature coincident with breaking. This temperature spike was followed by a cold signal of longer duration which was associated with the foam generated in the breaking process. The entire disturbance lasted approximately 12 s, after which the thermal boundary layer was reestablished.

Gasparovic *et al.* (1974) reported a temperature spike of 0.25°C due to a breaking wave measured at an incidence angle of 20° with a radiometer mounted on a moving surface vessel. Unlike Ewing and McAlister (1960), they did not observe a decrease in temperature associated with foam. They attributed its absence to the fact that, because the vessel was moving, the breaking wave did not remain in the measurement area long enough for the foam to appear. Simpson and Paulson (1980) made measurements at nadir from an instrument boom aboard the research platform *FLIP*. They reported that warm spikes of magnitude 0.3° were often associated with the steep part of waves.

Grassl (1976) and Schluessel *et al.* (1990) have cited the work of Clauss *et al.* (1970) as showing that the cool skin layer is effectively destroyed by wave breaking at wind speeds greater than 10 m s^{-1}. Grassl (1976) argues that a recovery time of about 10 s is too short for the skin layer to be reestablished between breaking events. Schluessel *et al.* (1990) state that the studies of Ewing and McAlister (1960) and Clauss *et al.* (1970) show that the skin layer can be reestablished within 10 to 12 s.

2 Infrared Imaging of Breaking Waves

All of these previous measurements were made with narrow field-of-view radiometers that provide a point measurement of temperature. To investigate the infrared signature of breaking waves further, we made measurements using an infrared imager which provides a two-dimensional map of surface temperature. The measurements were made in deep water aboard R/P *FLIP* in January 1992 off San Diego. The imager was an Agema model 880 LW infrared scanner operating at wavelengths of 8–12 microns with a noise equivalent temperature of 0.05°C. Equipped with a 40° field-of-view lens, the imager was mounted on an instrument boom 10 m above the sea surface at an incidence angle of 20°. In this geometry, the full image size was approximately 10 m by 10 m.

Figure 1 is a sequence of images of a breaking wave taken at night under conditions of large swell and moderate winds (significant wave height of 4.2 m, wind speed of 8 m s^{-1} at 10 m height). The elapsed time between each image is 0.32 s; time increases from left to right and from top to bottom. The breaking wave propagates from right to left, with the actively breaking crest appearing as a crescent

Fig. 1. Nighttime sequence of infrared images of a breaking wave showing apparent temperature change associated with the actively breaking crest and with the turbulent wake. Each frame is approximately 10 m by 10 m, and the time step between them is 0.32 s.

shape with a maximum apparent temperature difference of 0.4°C compared with the undisturbed surface. After the crest has spilled, a roughly circular patch is left behind, with an apparent temperature difference of about 0.3°C. This feature persists for only about 1 s, after which the background temperature is reestablished.

To determine if these apparent temperature changes were due to the disruption of the skin layer or a consequence of the extreme geometry and changed nature of the surface of a breaking wave, we compared nighttime images of a breaking wave like the one in Figure 1 with daytime examples. If the temperature increase seen in the nighttime images was due to disruption of the skin layer, then we would not expect to see a comparable temperature increase in the daytime images, since the skin layer is less well established during the day. On the other hand, if the effect was due to changes in the geometry and in the electromagnetic properties of the surface, then we would expect to see similar effects during the day.

In general, a temperature increase associated with the actively breaking crest region occurred both at night and during the day. However, the circular patch left behind after the wave breaks was seen only at night, when the cool skin layer was well established. These observations imply that the temperature change associated with the active whitecap is an apparent change, perhaps due to a combination of reflection from a different zenith angle and changes in emissivity due to increased surface roughness and air content. In contrast, the fact that the temperature change associated with the turbulent wake is seen only at night implies that that change is real and due to disruption of the skin layer.

3 Results and Conclusions

If the warm patch left behind by a breaking wave corresponds to its turbulent wake, then these infrared images may contain information on the dynamics of the breaking process itself. The simplest question to ask is if the patch size can provide a measure of the scale of the breaking process that produced it. As a first step toward answering this question, we analyzed 12 nighttime sequences of infrared images like those in Figure 1 containing individual breaking events. The speed of the actively breaking crest, estimated from the infrared images, was used as a measure of the scale of the breaking wave (Phillips, 1988). The "diameter" of the wake in the direction of propagation was used as the characteristic dimension of the wake. This one-dimensional measure was chosen over the two-dimensional area to avoid the complications that might arise in comparing short- and long-crested waves. Since the measurements of both the crest speed and the wake dimension were done manually, the average of three independent estimates (using adjacent frames within a sequence) was used. The standard deviation associated with the average was taken as an estimate of the error associated with the analysis.

The result is plotted in Figure 2 as the wake length versus the crest speed. As one might expect, the wake dimension increases with crest speed, implying that larger breaking waves produce larger wakes. A linear orthogonal regression and a quadratic curve fit to the data are also shown. Since the wavelength for linear deep water waves is proportional to the square of the phase speed, one might expect that the wake dimension would vary quadratically with the crest speed. For the limited range of these data, both types of fitting seem reasonable. The error bars correspond to the estimate of the errors associated with the measurements, as described above. The crest speeds for the individual breaking events analyzed ranged from 1 to 3 m s^{-1}. While these values may seem small for the open ocean, they are not inconsistent with the kind of mixed seas that we typically encountered; the breaking waves we observed were usually wind waves breaking on the crest of

Fig. 2. Characteristic length of the infrared signature of the wake of a breaking wave versus the speed of the actively breaking crest for 12 events. Both linear and quadratic curves represent the data well. See text for method used to determine error bars.

the large swell.

The turbulent wakes due to breaking waves that we observed persisted for roughly 1 s. As noted above, this result differs from previous reports of a skin layer recovery time of 5 to 10 s. One possible explanation for the discrepancy is that the skin layer recovery time is a function of wind speed. As mentioned above, previous investigators have used a recovery time of 10 s to argue that the skin layer is not present at high winds because it is destroyed by persistent breaking, which doesn't allow time for recovery. The percentage of breaking crests at a fixed point for a wind speed of 10 m s^{-1}, measured by several techniques, ranges from 10 to 20 percent (Jessup *et al.*, 1991). Thus one would expect several wave periods would elapse between breaking events in the same location, allowing the skin layer to reestablish itself even for a recovery time of 10 s. A recovery time of 1 s casts further doubt on the argument that the absence of the skin layer at high winds can be attributed to breaking alone.

While previous investigators have observed temperature spikes associated with breaking waves, they have also reported decreases in temperature associated with the foam left behind after breaking. We did not find a significant infrared signature due to residual foam in our comparisons of daytime video and infrared images. On the other hand, we did see an apparent temperature increase associated with the actively breaking crest, which may share some of the same electromagnetic properties with the residual foam.

The results presented in this paper suggest that the size of the turbulent wake left by a breaking wave can be used as a measure of the scale of breaking. They provide encouragement for further use of infrared imaging techniques to investigate the spatial and temporal scales of variability of sea surface temperature.

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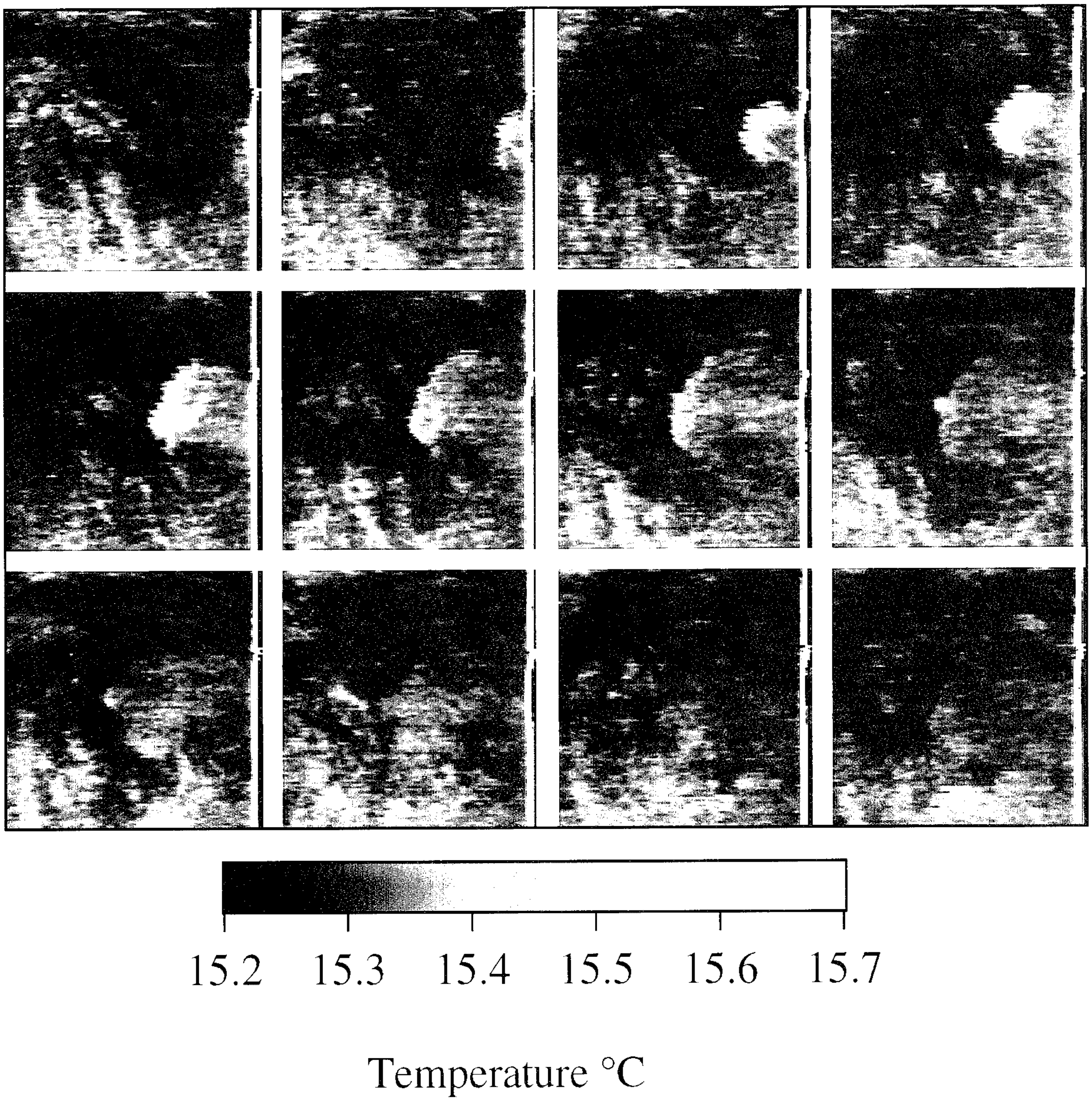

Figure 1. Nighttime sequence of infrared images of a breaking wave under moderate wind speed of 8 m/s and large swell (SWH 4.0 m). Time increases left to right, top to bottom; each frame is approximately 10 m by 10 m and the time step between them is 0.32 s. The roughly circular patch left behind after the wave breaks is interpreted as the disruption of skin layer due to the turbulent wake. The skin layer recovers in 1-2 s, in contrast to published recover time of 5-10 s.

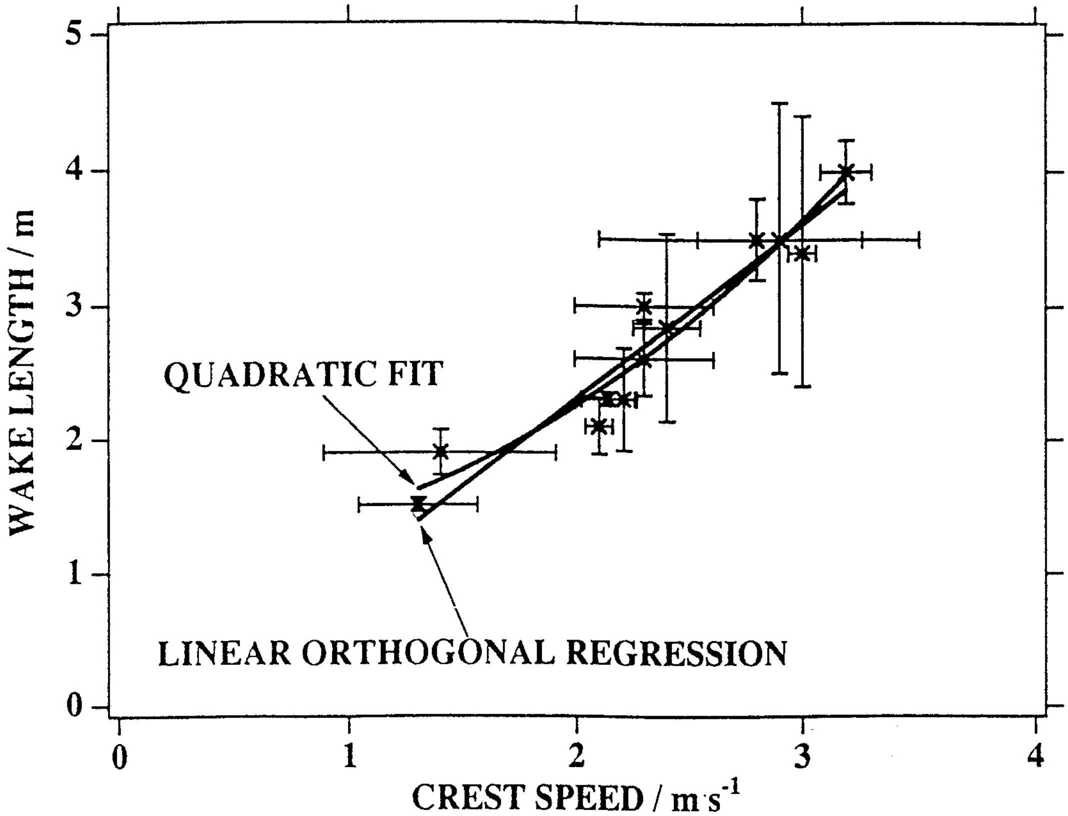

Fig. 2. Characteristic length of the infrared signature of a breaking wave versus the speed of the actively breaking crest for 12 events. Both linear and quadratic curves represent the data well. See text for method used to determine error bars.

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